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A parametric method to synthesize wind turbine sounds

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Abstract
The annoyance to wind turbine sound is today well known. There is no doubt that increased sound pressure level causes in general an increased annoyance. However, when it comes to additional descriptors of the wind turbine sound, such as e g equivalent frequency spectrum or amplitude modulation, there is no consensus on what parameters that are most important. In the research project Wind Turbine Noise Effects on Sleep (WiTNES) there was a need for 8 hour long sound signals from wind turbines that were completely free of extraneous sounds. Recordings from reality are difficult to maintain free from disturbances. Instead a parametric synthesis method was developed that is capable of creating wind turbine sounds of arbitrary length. The sounds can be designed in terms of equivalent frequency spectrum, what frequency bands that have amplitude modulation as well as frequency dependent amplitude modulation strength and variation. Recordings of wind turbine sounds at immission distances from different wind turbine types were used to find relevant values for the parameters. This paper describes the synthesis method and some examples of input parameters.

Keywords: Wind turbine noise, Wind turbine sound, Auralization

1 INTRODUCTION

Wind turbine sound can lead to self-reported sleep problems and annoyance among people living in the vicinity of the turbines [11, 4]. The amplitude modulation (AM) of wind turbine sounds is believed to have a strong influence. Amplitude modulations are an easily perceivable sound characteristic associated with a higher risk annoyance [1, 12]. However, compared to annoyance we know rather little on how sleep is affected by wind turbine noise. Sleep studies require the ability to play back a wind turbine sound that has a high similarity to what nearby residents could be exposed to, and at the same time contain no extraneous sounds that may "falsely" trigger psychological or physical response.

Early in the project it was concluded that it is unlikely that we can find sufficiently long recordings that can be used directly in the sleep studies, especially since the recordings should not include strong wind noise, birdsong, rainfall, or other distinct background noise events. The use of short sound files, on the other hand, can lead to perceived periodicity by the subjects, and may thus affect the final results. Instead of using direct recordings, the project chose to find a method to synthesise wind turbine sounds from data representative to wind turbine type and meteorological situation. With synthesised files it is also possible to control exposure levels, frequency spectrum and various amplitude modulations.

In the following, key parameters are presented for wind turbine sounds. The parameters can be used to synthesize sound files of arbitrary length, and with a sufficiently high quality for sleep studies. This paper describes the method to synthesise wind turbine sound files that have been used in sleep studies in the WiTNES project to study if wind turbine noise at the Swedish requirement limit, L_{eq}= 40 dBA, can influence sleep. The sleep study, including descriptions of the chosen noise exposures, the reproduction system and sleep disturbance evaluation methods, will be presented in future papers.

2 AMPLITUDE MODULATION IN WIND TURBINE SOUNDS

Aerodynamic sound is generated when the rotor blades of a wind turbine move through the air, producing a broad band rhythmic, i.e. amplitude modulated, sound. . Local meteorological conditions at the the wind turbine rotor influences the character of the emitted sound. In certain meteorological conditions, wind shear can lead to local stall in the outer parts of the rotor area, inducing strong amplitude modulation and significantly higher sound pressure levels in the low frequency region [8]. Previous studies also show large differences in sound between wind turbine types [7], indicating that there are important differences in acoustic behaviour between wind turbine models, differences that are modulated by the local meteorology with respect to both space and time.

3 RECORDING SITES

There are detailed semi-empiric models of noise radiation from wind turbines in the literature (see e g [9, 6]) with reasonable fit to experimental data. However, these prediction schemes require detailed information that in general is not publicly available. This in combination with the large observed differences in radiated sound power from wind turbines reported in e.g. [7] makes it unlikely that there exists a general set of any physical parameters that can be used to predict the sound from all wind turbine models.

The WiTNES project has collected four datasets at different locations in Sweden, where measurements and recordings has been made on dwellings near single wind turbines. All recordings were made with equipment fulfilling the requirements for a Type 1 sound level meter. All wind turbines included here have been verified in measurements regarding their sound power level, i.e. they fulfil the manufacturer's specifications. The locations are briefly described in Table 1. The locations in the table could thus be argued to possess a large acoustic variation, even though it does not represent all available wind turbine types or manufacturers. The temporal influence of meteorological variation on wind turbine sounds is implicitly included in some of the data sets since recordings were made over long time.

Table 1. Brief description of the immission recording sites.

Location	Power (MW)	Turbine diameter (m)	Hub height (m)	Distance (m)	Number of recordings	Total recording length	Calendar time
1	1.8	70	65	550	7005	~117 h	~1 month
2	2.0	90	80	580	2	3.5 h	4 h
3	2.0	90	105	500	850	~7 h	~1 month
4	2.4	110	95	650	30	30 min	~8 h

3.1 Equivalent sound level spectra

It is not the absolute equivalent sound level spectrum that is of main interest; the equivalent level spectrum shape is more important. Therefore, the equivalent sound level in each 1/3 octave band was normalised with L_{eq} (the total equivalent sound level, unweighted with respect to frequency) to get the partial level of each 1/3 octave band through

$$L_{eq,partial,i} = L_{eq,i} - L_{eq} \quad (1)$$

for each 1/3 octave band i between 20 and 5000 Hz. The resulting partial spectra for chosen short clips from locations 1-4 are shown in Figure 1. The clips were chosen for their perceptually strong amplitude modulation. All locations follow a similar spectrum shape, albeit with spectrum variations. The differences are larger at higher frequencies but those differences are related to background sounds such as wind hiss, birdsong and other disturbances. Note that the spectra shown in Figure 1 are not mean values for various meteorological situations or over different time periods for the same turbine. They describe a sort of worst-case scenario, chosen for their subjectively strong level and distinct amplitude modulation. The recordings evaluated in Figure 1 sound subjectively different despite the similar equivalent spectra, and it is thus necessary to analyse the recordings in the time domain to find their amplitude modulation (AM) characteristics.

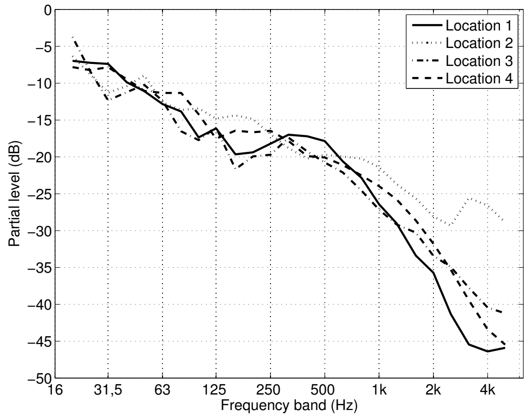

Figure 1. Evaluated partial sound pressure levels in 1/3 octave bands for all locations.

3.2 Amplitude modulation parameters

The amplitude modulation is commonly described using the A-weighted signal, but here the amplitude modulation is studied in the 1/3 octave bands between 20 and 5000 Hz. A few examples of individual 1/3 octave bands for location 3 are shown in Figure 2 to demonstrate the main aspects. However, evaluations were done for all 1/3 octave bands. In the graphs a 'Fast' time weighting was added to the signal for visibility. The A-weighted total sound level using the same time weighting is also shown for reference. After making similar graphs for the other locations in Table 1 it was concluded that the amplitude modulation in individual frequency bands is dependent on turbine type. In the figure a generalised time modulation shape is included. This generalised shape is deduced after visually evaluating over 100 individual pass-bys for the different locations and frequency bands, and it uses three parameters (as visualised in Figure 2):

1. Modulation strength
2. Top width
3. Rising slope of the modulation peak

Interestingly the decay slope of the modulation peak seems constant for the different wind turbine types included here. The evaluated value is close to 20 dB/s for individual 1/3 octave bands that includes amplitude modulation. This is a significantly slower decay rate than for a 'Fast' time weighting, which has a decay rate of 35 dB/s. The three amplitude modulation parameters shown in Figure 2 vary over time in a seemingly random way. Meteorological effects between wind turbine and dwelling probably partly cause this, since propagation distances are generally 500 m or longer.

Limited listening tests held with a few experienced listeners showed that the modulation strength has largest influence on the subjectively perceived sound; the rising slope and the top width has less influence. This corresponds well with findings in other listening tests [13].

3.3 Evaluation method of amplitude modulation strength

Currently there is no generally accepted method for amplitude modulation strength evaluation. In this paper we adopt the formulation used in [5]:

$$\Delta L = 20\log\left(\frac{p_0 + p_f}{p_0 - p_f}\right) \tag{2}$$

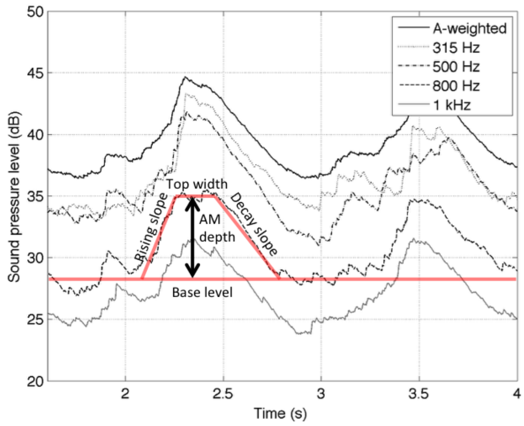

Figure 2. Time sequences for individual blade pass-by for location 1 in selected 1/3 octave bands.

where p_0 is the steady root mean square (RMS) value of the signal, corresponding to the equivalent level, and p_f is the RMS value of the signal at the blade pass-by frequency.

The blade pass-by frequency has been evaluated using the Discrete Fourier Transform (DFT) of the signal magnitude of 10 s recording clips. The DFT has rather coarse frequency resolution when working with short signal lengths. A 10 s sound clip, as used here, gives a frequency resolution of 0.1 Hz, which in turn leads to a resolution in rotations per minute (RPM) of 2 RPM. A resolution of 0.1 RPM is needed to create realistic sound files. To obtain this, a combination of the Discrete Fourier Transform (DFT) and direct calculation of the Fourier coefficients has been used, a technique usually called Zoom-FFT [10].

The amplitude modulation in each 1/3 octave band at the blade pass-by frequency for the 10 s clip can then be evaluated by a single-frequency DFT. A Hamming window together with 50 % signal overlap has been used for all signal evaluations in this paper.

The evaluation method for amplitude modulation used here is similar to the Reference Method proposed by the Institute of Acoustics [3] in the overall approach, but there are significant differences in the method details. The IoA Reference Method uses three distinct frequency bands (50-200, 100-400 and 200-800 Hz), while the method presented here uses 1/3 octave bands. Both methods use Fourier Transform of the signal magnitude to find the blade pass-by frequency. Our formulation of the AM strength (above) is evaluated in the frequency domain while the IoA Reference Method is evaluated after an inverse Fourier transform.

3.4 Evaluation results for amplitude modulation

The method presented above was applied to the full data set of all locations in Table 1. The left graph in Figure 3 shows a histogram of the evaluated A-weighted AM for all locations. The histogram uses proportional occurence instead of absolute values in order to facilitate comparisons between the locations since they have very different overall recording times.

However, it was suspected that high AM strengths at low frequencies could be caused by wind noise. Therefore a linear regression was made between individual 1/3 octave band AM and the A-weighted AM using a first-order polynomial. Note that this does not limit the importance of amplitude modulation at low frequencies, the correlation states *if* AM at low frequencies are simultaneous with A-weighted AM. The right graph in Figure 3 shows the AM strengths only for the 1/3 octave bands where $R^2 \geq 0.2$. Note that this choice only applies to the existence of AM, not to the absolute equivalent sound level nor the equivalent frequency spectrum. Different amplitude modulation spectra, as exemplified in Figure 3, are probably linked to the subjectively qualitative differences that exist between sounds from different wind turbine types [14]. The figure clearly shows that

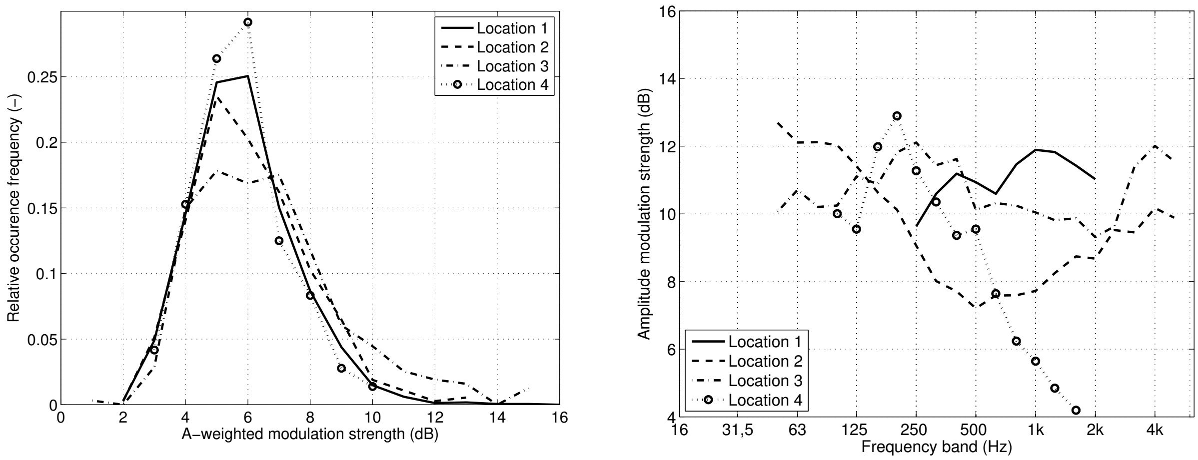

Figure 3. Evaluated amplitude modulation for the locations. Left: Relative occurence frequency of A-weighted AM strength. Right: AM strength in 1/3 octave bands with $R^2 \geq 0.2$.

some turbine types show strong amplitude modulation in the low frequency region (below 200 Hz), while other types do not.

The chosen methodology focuses on the 'worst case' situations for amplitude modulation strength, and which frequency bands that are modulated. There will certainly be periods of time at any dwelling where the wind turbine sound will be less pronounced, less loud and thus less annoying. However, little is known of which time base or statistical percentage level should be used to assess annoyance or sleep disturbance at dwellings. This is also noted by the Institute of Acoustics in their report [3].

4 Synthesis of wind turbine sounds

4.1 Description of the synthesis method

The sound file synthesis was designed to give representative sounds for an outdoor situation in free field, and it used the flow chart in Figure 4. The input data used rotation frequency and number of blades for the turbine as global information to get blade pass-by frequency. Amplitude modulation data through modulation strength, top width and rising slope were given in each 1/3 octave band. Each band was adjusted to its target equivalent level after the modulated 1/3 octave band signal was constructed, i.e. the time-varying signal was evaluated for its equivalent level, and adjusted to its desired value. Realistic parameter values for the modulation strengths and equivalent levels were taken from the evaluations in section 3.4.

The individual blade passages need to be non-identical to sound real. A two-step randomisation for the modulation strength was introduced to make the sounds more realistic:

1. A random amplification of the wide band amplitude strength that describes each individual blade pass-by strength. The amplification is given in dB, and follows a normal distribution with zero mean value and 1 dB standard deviation. Note that the amplification can be below zero, i.e. individual blade passes are damped.

2. The wide band random amplification in step 1 was scaled for each 1/3 octave band individually using 1/4 of the modulation strength as standard deviation for each 1/3 octave band respectively. The actual modulation strength for all 1/3 octave bands are thus correlated with each other. In other words, a strong blade pass by is strong in all 1/3 octave bands.

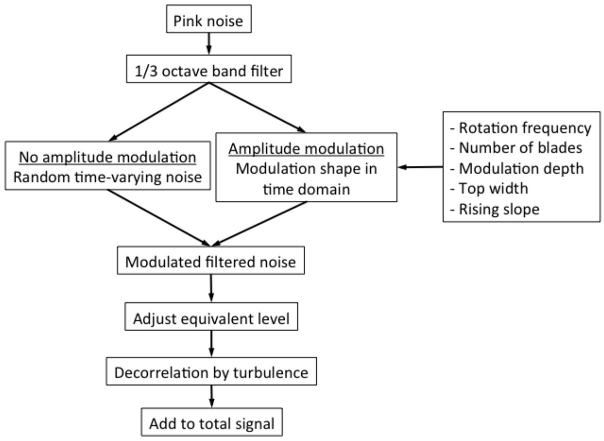

Figure 4. Flow chart of the sound file synthesis.

At a real wind turbine site the transmission path from source to receiver is never constant. A random time delay (normally distributed with zero mean value and standard deviation 50 ms) was also added between the individual blade pass-bys to mimic variations in sound travel time between wind turbine and receiver. A second normally distributed time delay with zero mean value and 20 ms standard deviation was furthermore added to each 1/3 octave band individually. This last random time delay was uncorrelated between the 1/3 octave bands.

Not all 1/3 octave bands show AM for real wind turbines. For bands with no AM a time-varying shape using one random number per minute and one uncorrelated random number per second was used. The time envelope was then linearly interpolated over time to avoid sudden sound strength changes. The equivalent levels for 1/3 octave bands without AM were then adjusted in the same way as for a 1/3 octave band with AM.

The influence of turbulence along the transmission path was modelled similarly to the method used in [2]. The turbulence fluctuations result in amplitude variations also on a shorter time scale than that of a blade passage. Air absorption along the propagation path was also introduced using the method described in the standard ISO 9613-1.

Experienced listeners who are used to wind turbine sounds have been used in the development of the synthesis method to evaluate the subjective quality of the resulting wind turbine sounds. The final method, which has been described here, have been found to produce sounds that subjectively sound like wind turbines. Listening tests to corroborate this statement will be performed in another project.

Other noise sources, such as background noise caused by wind in nearby vegetation or distant road traffic, can be added to make the sound more realistic. However, any such addition would have an impact on the total level and the AM of the final sound clip.

4.2 Evaluation of synthesized examples

Three test cases were designed to validate that the synthesis method actually can produce sound files with arbitrary AM:

1. A frequency independent AM, i.e. a modulation that is equally strong in all 1/3 octave bands
2. AM exists in the 1/3 octave bands between 160 and 500 Hz
3. AM in the 500 Hz 1/3 octave band

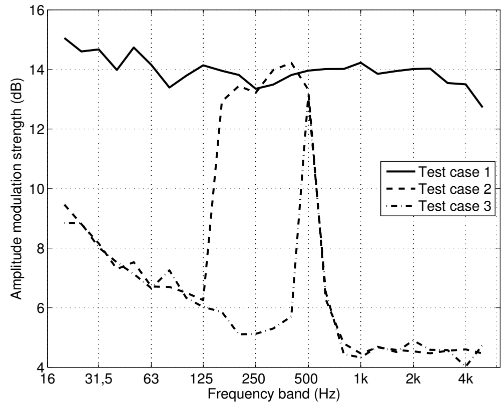

Figure 5. Evaluated AM of synthesised wind turbine sounds according to test cases 1-3.

The AM strength was varied between zero (no AM) and the maximum value found from the real life recordings as described in section 3.4. All test cases used 8 sound files of 5 minute length with AM nominal range from 0 dB up to 14 dB with 2 dB step. The equivalent level spectrum of the signals was set to a spectrum similar to the spectra shown in Figure 1.

Evaluated results from all test cases are shown in Figure 5, where it can be seen that the AM evaluated from the synthesized sound files follow the used input data. The AM shown in the figure are for 90 % occurrence levels. Variations of around 1-2 dB can be seen for test case 1 (AM independent of frequency), at the lowest frequencies somewhat more, but this variation is expected since the synthesis method includes randomisation of the blade pass-bys. For test cases 2 and 3 the AM strength is high in the intended 1/3 octave bands, and low outside of these bands. The method is thus shown to be capable of creating high AM in broad band, bandpass in two octave bands, and in one single 1/3 octave band.

The equivalent level spectrum of the synthesized file was well within 1 dB from the desired value for all 1/3 octave bands up to 2 kHz. The differences were larger at higher frequencies, which was probably linked to the air absorption. The low sound levels at high frequencies makes these differences unimportant in subjective tests.

This shows that the presented synthesis method is capable of producing sound files with arbitrarily desired equivalent level spectrum *and* amplitude modulation spectrum simultaneously. This synthesis technique can thus be an essential tool for creating realistic stimuli in the subjective listening tests, or in sleep studies.

5 Discussion and conclusions

An evaluation method for amplitude modulation from in situ wind turbine sound recordings has been presented in this paper. The proposed method only uses the sound files, and is shown here to be applicable both on A-weighted signals as well as 1/3 octave band signals. Evaluations on sound recordings at dwellings from four wind turbine locations in Sweden showed that the tirbines have similar equivalent level spectra, but different amplitude modulation characteristics. The most important conclusion was that the four locations showed significantly different amplitude modulation strength spectra, which is probably linked to their subjectively perceived sounds.

The synthesis method that has been described in this paper is shown to be capable of producing sound files that have an equivalent level spectrum and arbitrary amplitude modulation that can be tailored to perform subjective listening tests or sleep studies. Experienced listeners have stated that the synthesized sounds are subjectively close to real wind turbine sounds. The synthesis method gives a large advantage over using recordings, since it is free from unwanted extraneous sounds.

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